N92-22777

Gates Energy Products

GATES AEROSPACE BATTERIES

FAULT TREE ANALYSIS

NiH_2 AEROSPACE CELLS

FOR LEO MISSION

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Abstract

The Fault Tree Analysis (FTA) is one of several reliability analyses or assessments applied to battery cells to be utilized in typical Electrical Power Subsystems for spacecraft in LEO missions. FTA is generally the process of reviewing and analytically examining a system or equipment in such a way to emphasize the lower-level fault occurrences which directly or indirectly contribute to the major fault or top-level event. This Qualitative FTA addresses the potential of occurrence for five specific top-level events: **HYDROGEN LEAKAGE** through either discrete leakage paths or through pressure vessel rupture; and, four distinct modes of performance degradation - **HIGH CHARGE VOLTAGE, SUPPRESSED DISCHARGE VOLTAGE, LOSS OF CAPACITY,** and **HIGH PRESSURE.**

Relationship Between Reality, System Model, and Decision Process

Figure 1 schematically depicts one decision making process wherein we may explore the relationship between reality, some model of our system, and the decision process. **REALITY** is defined by a system of internal and external boundaries. **OUR PERCEPTION OF REALITY** is defined by the Fault Tree. **BASIS FOR DECISION**, in this case some measured acceptance of risk, is justified by the degree to which redesign, qualification tests on parts and materials and discrete inspection or test points were utilized. Figure 2 illustrates a generic system to be analyzed with external and internal boundaries. Hence, **ITEM E** is the Power Sub-System and **ITEM F** is the Battery Assembly wherein items a-to-r would be individual cells.

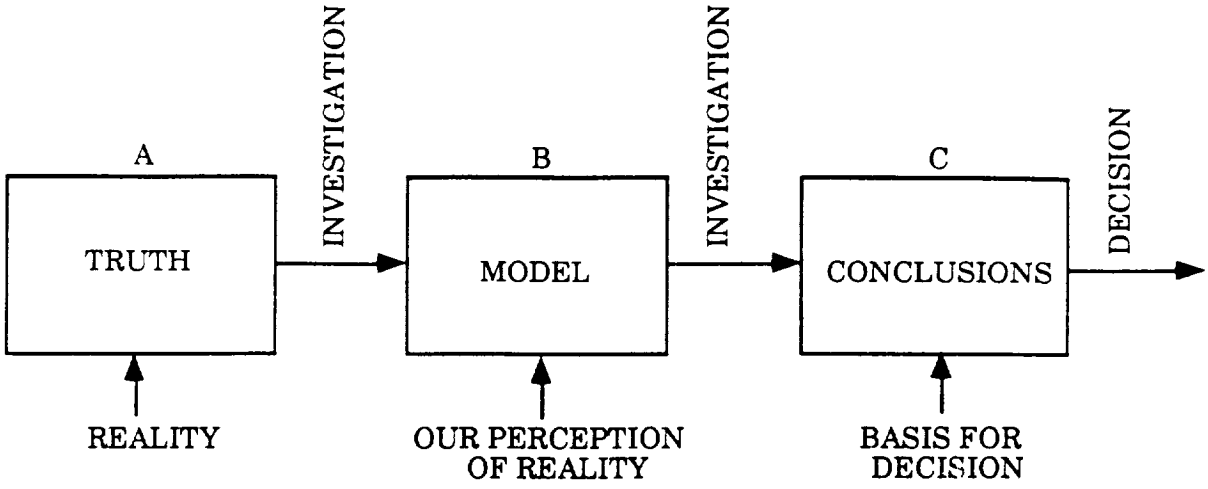

FIGURE 1: RELATIONSHIP BETWEEN REALITY, SYSTEM MODEL, AND DECISION PROCESS

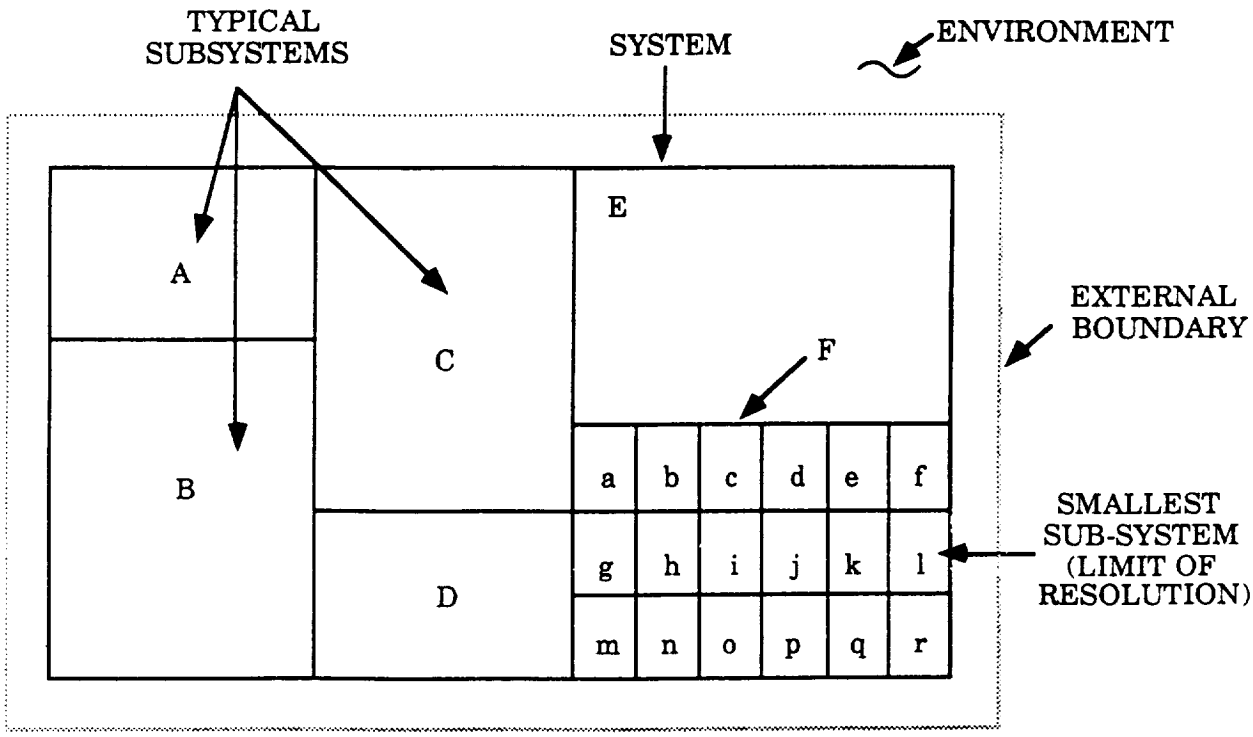

FIGURE 2: SYSTEM DEFINITION: EXTERNAL AND INTERNAL BOUNDARIES

The external boundaries describe the interface which the battery assembly, and ultimately the individual cells, experiences in the LEO mission profile. A typical profile requires continuous duty in combination with a solar array to store energy for use during peak power demands and eclipse periods, and may include:

a) 35% Depth of Discharge within 35 to 40 minutes followed by a C/1.67 rate recharge in 50 to 60 minutes
b) nominal temperature range of 0 to 30°C
c) a dynamic mechanical environment during the launch phase including a wide, but well defined spectrum, of random vibration; typical sustained acceleration of 20 g; and broad range of shock spectra
d) life and reliability requirements including on station calendar life of 5.5 years MTBF and a design cycle life of 41,000 cycles

The internal boundaries are described by the cell design and include the rudimentary details such as pressure vessel material composition and thickness, and the electrochemical characteristics of the nickel-hydrogen couple as well as the decision to use a recirculating stack design.

The degree to which a fault described in the Fault Tree may result in battery failure or performance degradation is masked somewhat by the availability of in-flight data; this could be equated to the Limit of Resolution in our generic system of Figure 2. The degree to which the actual mission profile conforms to the intended profile combined with the ability of the NiH_2 cell to perform its intended function, irregardless of the nonconformance, is a measure of "robustness of design."

Basics of Fault Tree Analysis (FTA)

Figure 3 illustrates symbols typical of those used in our NiH_2 FTA; numerous others are available see Reference 2. The **rectangle** contains a brief description of the top-level event and appears at top of the tree. The **rectangle** is also used in this tree to signify a lower-level event and contains a brief description; these lower-level events occur throughout the tree and have both their input and output from a logic gate. The **circle** represents a basic or the lowest-level event which may cause a fault to occur and is used as an input to a logic gate. The **diamond** is a transfer

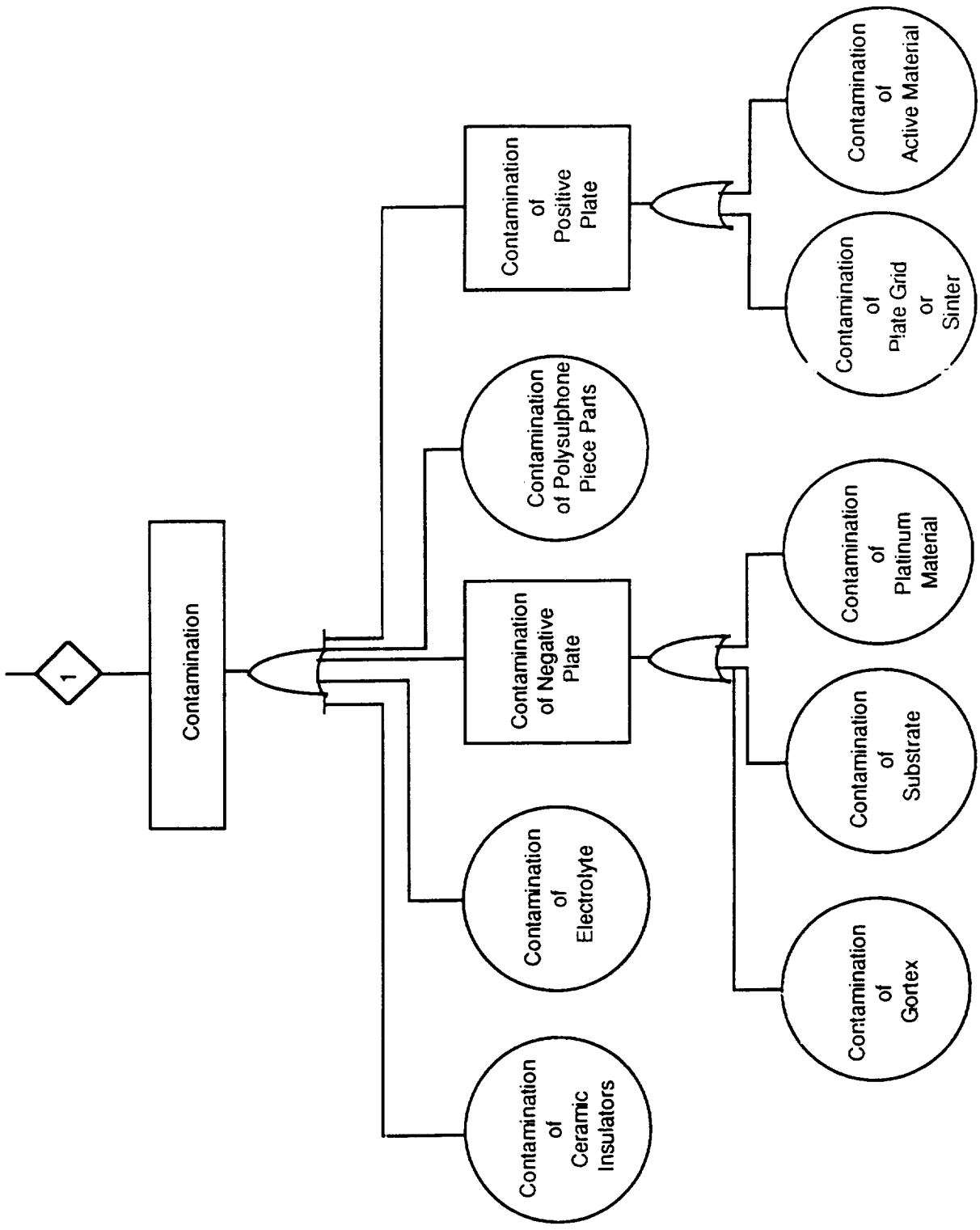

FIGURE 3: FAULT TREE SYMBOLOGY

function and is used to signify a connection between two or more sections of the fault tree. Logic Gates include the **OR Gate** for which output occurs when one or more of the input events occur; whereas, the **AND Gate** only occurs if all the inputs exist simultaneously.

Failure Effects, Failure Mode, and Failure Mechanism

Understanding and defining how a specific failure mechanism produces a discrete failure mode which may effect system operation is important for determining the proper inter-relationships among the events. In addition, the orientation of the analysis, that is whether to concentrate on system response symptoms or specific signatures generated by active components, determines both the success of the analysis and the effectiveness of resulting remedial actions. Failure Effects: what are the effects of the failure, if any, on the system. Failure Mode: what aspect, condition, or position is of concern. Failure Mechanism: what particular mechanism or vehicle prompts the failure mode to occur and what likelihood of occurrence exists. Thereafter, failures may be classified as to component, environmental, human, or software. Component failures occur at the lowest level of examination and may in fact be discrete parts or materials. Environmental failures occur when the system is placed in an environment which the system was not designed to operate in and where overstress has now occurred. Human failures occur due to operator error and are most difficult to quantify given the unpredictably of humans in the elevated stress levels typically accompanying sophisticated, high reliability systems. Software failures are simply errors in the controlling software, but may be considered a sub-set of human failures or component failures. Notwithstanding these failure definitions, their existence simply becomes the further definition of internal and external boundaries of the system under analysis.

Top-Down Approach of the Fault Tree versus Bottoms-Up Approach of the FMECA

The top-down approach of the FTA presupposes sufficient examination of the system to enumerate the top-level events or major system performance failures. Thus, the examination and resulting analyses are limited to events which cause the top event to occur. This deductive approach postulates the opportunity for top level failure thereafter reconstructing events or behavior at the lower levels which contribute to this failure. The bottoms-up approach of the FMECA is inductive in

nature. This approach postulates numerous faults or initiating conditions and then attempts to determine the effect of that fault or condition on system operation and integrity. Generally, the FMECA tends to be initially more descriptive as a risk analysis and risk reduction tool because their format typically includes existing/projected compensation or control measures.

Qualitative Fault Tree for NiH_2 LEO

The discussion of faults versus failures necessarily assumes that the fault condition is of sufficient significance and magnitude to cause upper level failure events. Therefore, the role of various contaminants is not an idle reference in the fault tree of Figures 4 thru 22. There is no further assumption nor is there an attempt to yet quantify the level of contamination since some contaminants in small ppm may cause significant events which may lead to failure. No further assumption as regards passive versus active components and their significance is made either. When we analyze the pressure vessel for catastrophic burst and find the present design to leak before burst, there can not be an accompanying assumption which relegates this vessel to a passive component. The fault tree clearly shows a leaking pressure vessel to be an active contributor to upsetting the electrochemistry of the nickel-hydrogen couple which may eventually lead to either outright failure or performance degradation.

Five specific primary faults or top-level events addressed in the fault trees of Figure 4 are: **HYDROGEN LEAKAGE** through either discrete leakage paths or through pressure vessel rupture (discounted as a potential failure through both this analysis and the Fracture Control Plan); and four distinct modes of performance degradation (1) **HIGH CHARGE VOLTAGE, (2) SUPPRESSED DISCHARGE VOLTAGE, (3) LOSS OF CAPACITY,** and **(4) HIGH PRESSURE.**

Hydrogen Leakage

The critical fault, hydrogen leakage, was created in the classical fault tree analysis. By assuming the worst case scenario it was determined that the hydrogen leakage was and is the worst possible fault. All construction techniques were assessed from the top down to determine the different paths the leakage might occur. This event is typical of most NiH_2 pressure vessels and presents a generic path of construction criticality. By placing probabilities in each of the

lower fault events a manufacturer will be able to construct a detailed quantitative fault tree.

High Charge Voltage

This fault is divided into three generic failure modes of which two are identical to Loss of Capacity. These generic failure modes are further divided into specific failure modes which can be identified or traced back to respective FMEA failure modes. Some of these failure modes have been traced to their failure causes. These expanded fault trees may have no failure modes associated with them because either they are failure causes or are under review for inclusion into the growing Operational FMEA database.

High Pressure

Only two generic failure modes cause high pressure and one is unique to this fault. The flooding of the negative membrane is an operational fault that is a result of various contamination failures. We do not have FMEA worksheets filled out for contamination as it usually is identified in various FMEA worksheets as a failure cause.

Loss of Capacity

This fault tree is the least extensive of the operational critical faults. This is because it is associated with wearout mechanisms of the NiH_2 battery cell that are not modeled and has duplicity in other failure modes. The purpose of this fault tree is to show unique failure mechanisms associated with just Loss of Capacity. The loss of capacity has been divided into two larger groups of generic failure modes. These in turn have been broken down into other root causes and easily identifiable failure modes.

Suppressed Discharge Voltage

This fault tree is broken down into three specific failure modes identified by the operational FMEA worksheet numbers and one failure mode associated with NiH_2 wearout. A particularly interesting feature of this fault tree is that both hard and soft shorts can be caused by conductive particles. The conductive particle fault tree shows how these particles can be inherent to a fault process or introduced as foreign particles from material handling.

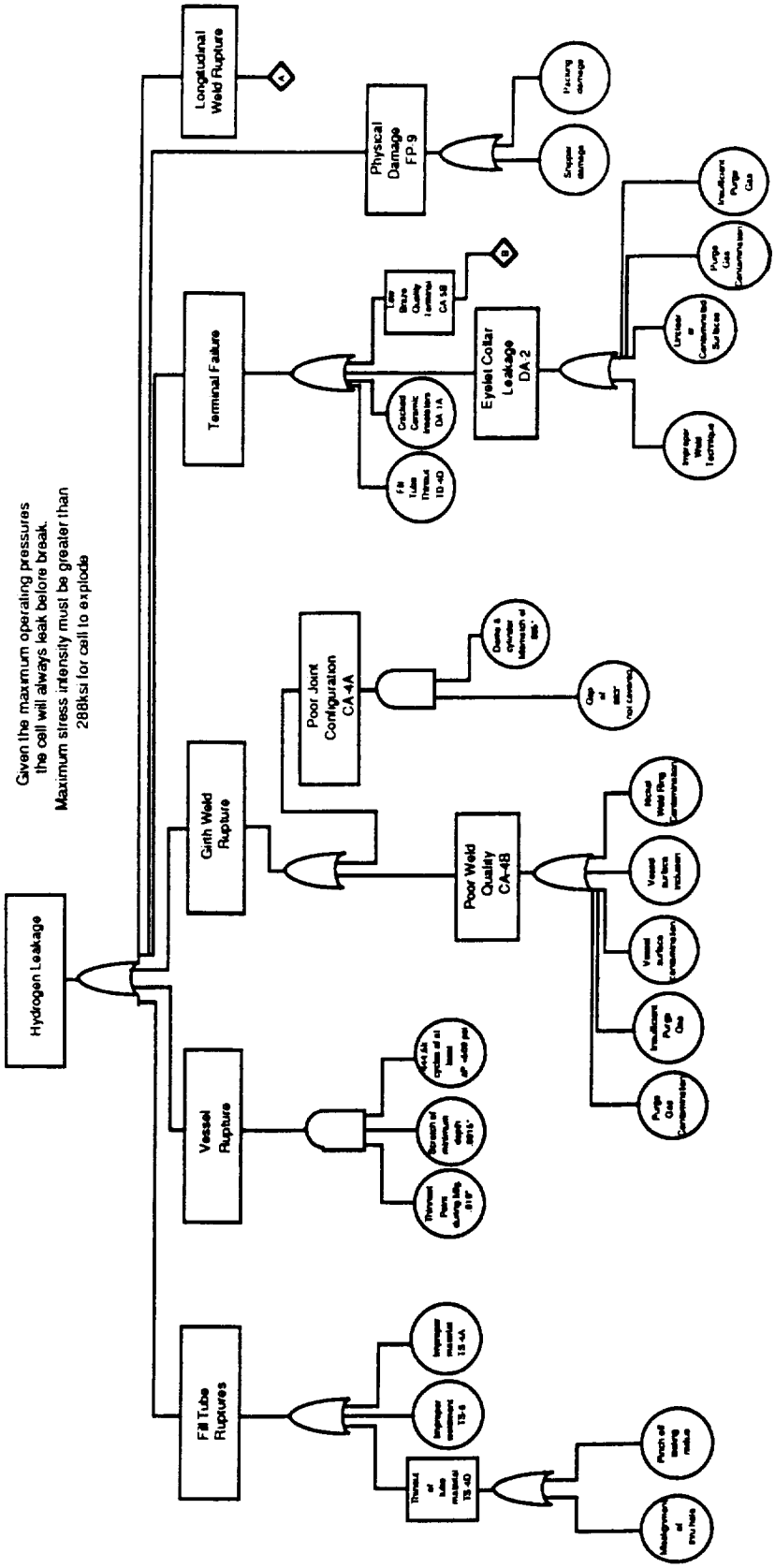
Given the maximum operating pressures
the cell will always leak before break.
Maximum stress intensity must be greater than
288ksi for cell to explode
Hydrogen Leakage
Longitudinal Weld Rupture
Physical Damage FP-9
Terminal Failure
Eyelet Collar Leakage DA-2
Girth Weld Rupture
Poor Joint Configuration CA-4A
Poor Weld Quality CA-4B
Vessel Rupture
Fill Tube Ruptures

FIGURE 4

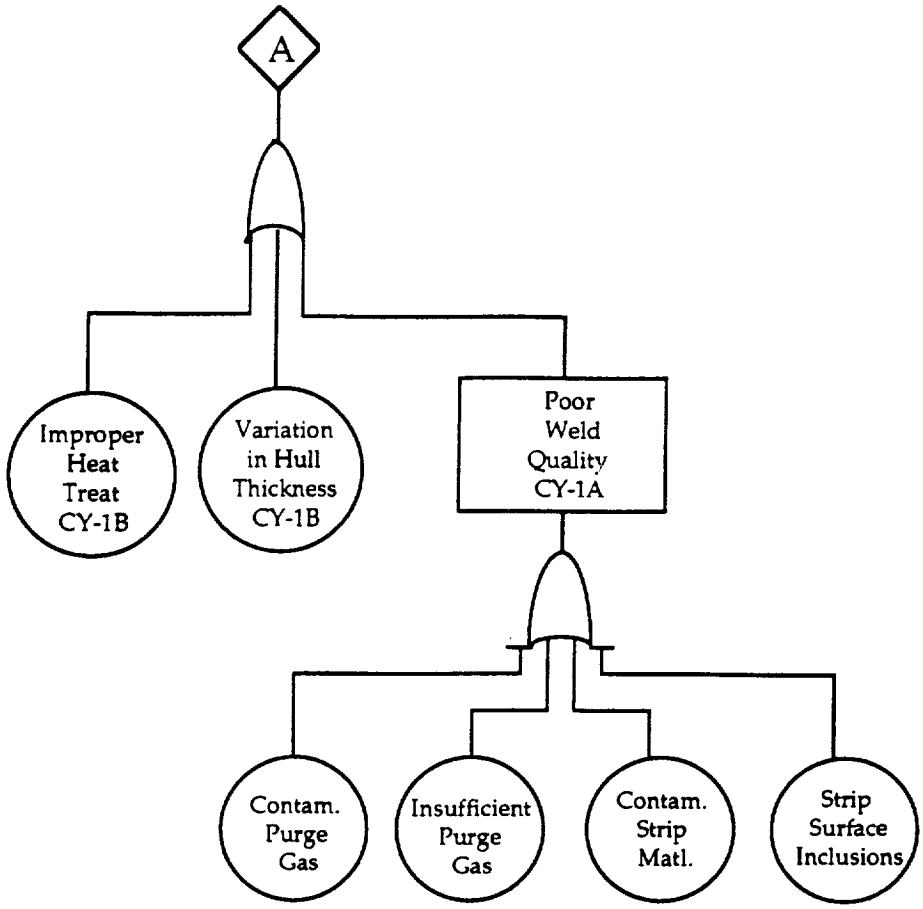
A
Improper Heat Treat CY-1B
Variation in Hull Thickness CY-1B
Poor Weld Quality CY-1A
Contam. Purge Gas
Insufficient Purge Gas
Contam. Strip Matl.
Strip Surface Inclusions

FIGURE 5

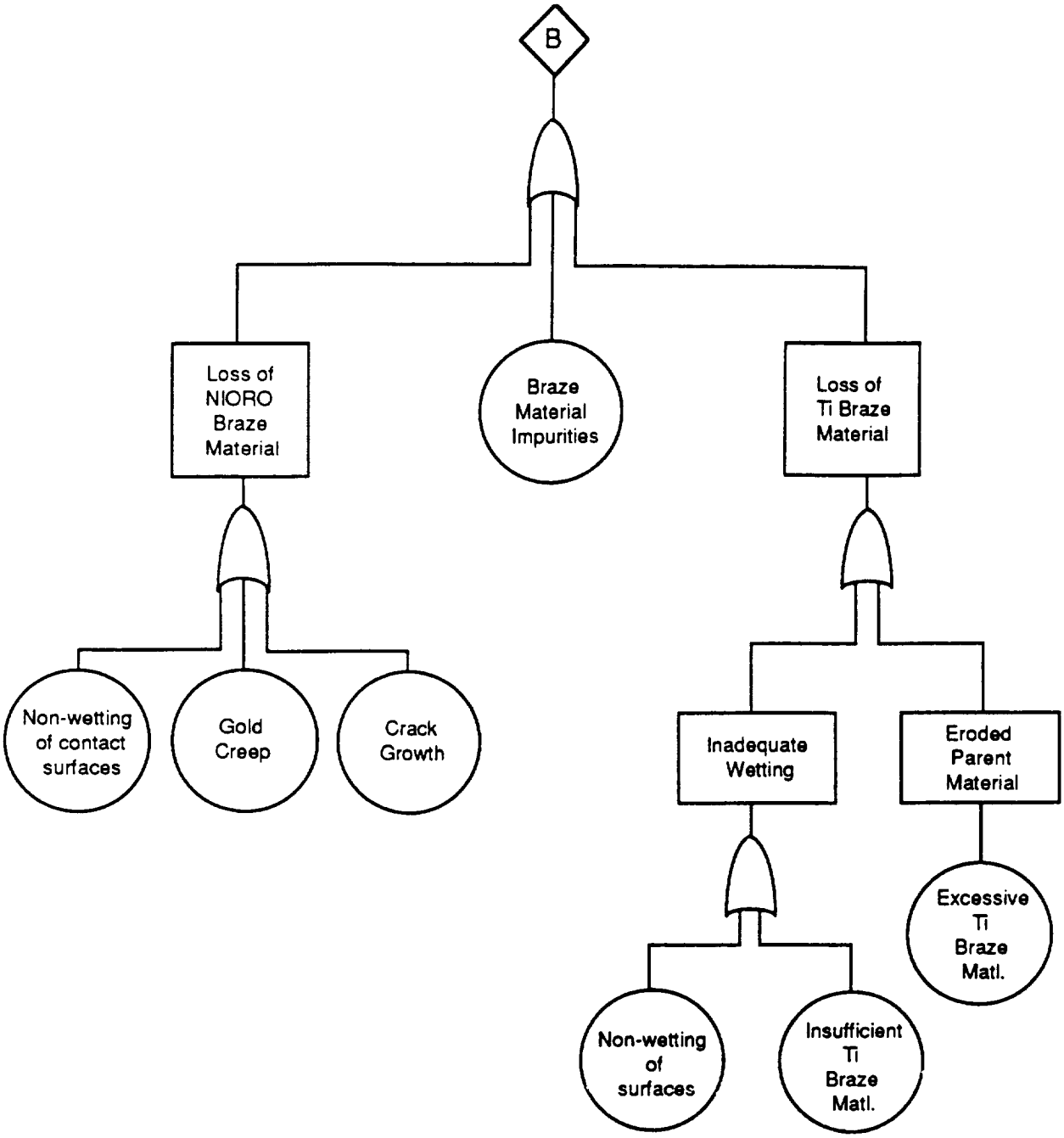
B
Loss of NIORO Braze Material
Braze Material Impurities
Loss of Ti Braze Material
Non-wetting of contact surfaces
Gold Creep
Crack Growth
Inadequate Wetting
Eroded Parent Material
Excessive Ti Braze Matl.
Non-wetting of surfaces
Insufficient Ti Braze Matl.

FIGURE 6

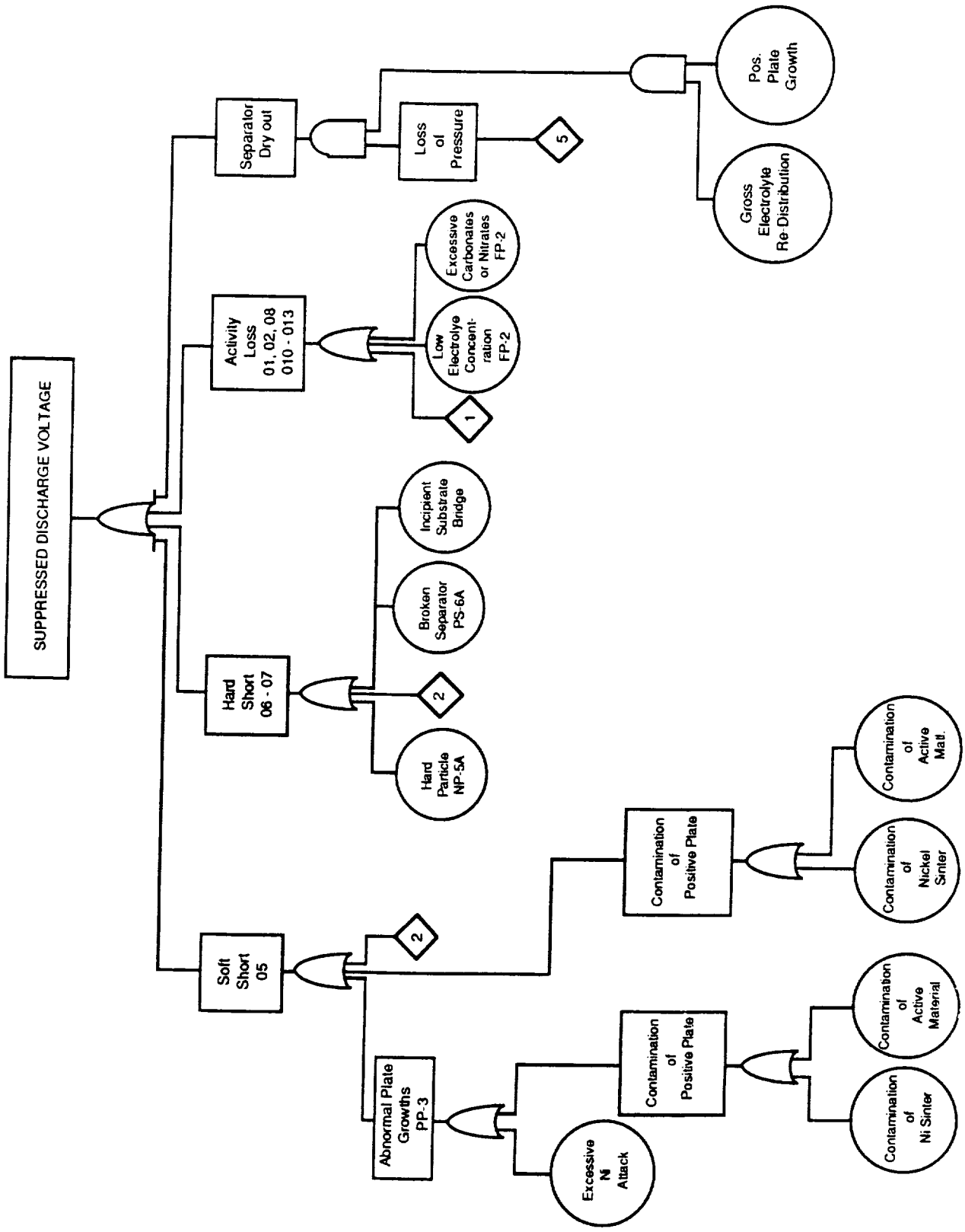
SUPPRESSED DISCHARGE VOLTAGE
Separator Dry out
Loss of Pressure
5
Pos. Plate Growth
Gross Electrolyte Re-Distribution
Activity Loss 01, 02, 08 010 - 013
Excessive Carbonates or Nitrates FP-2
Low Electrolye Concent-ration FP-2
1
Hard Short 06 - 07
Incipient Substrate Bridge
Broken Separator PS-6A
2
Hard Particle NP-5A
Soft Short 05
2
Contamination of Positive Plate
Contamination of Active Mat.
Contamination of Nickel Sinter
Abnormal Plate Growths PP-3
Contamination of Positive Plate
Contamination of Active Material
Contamination of Ni Sinter
Excessive Ni Attack

FIGURE 7

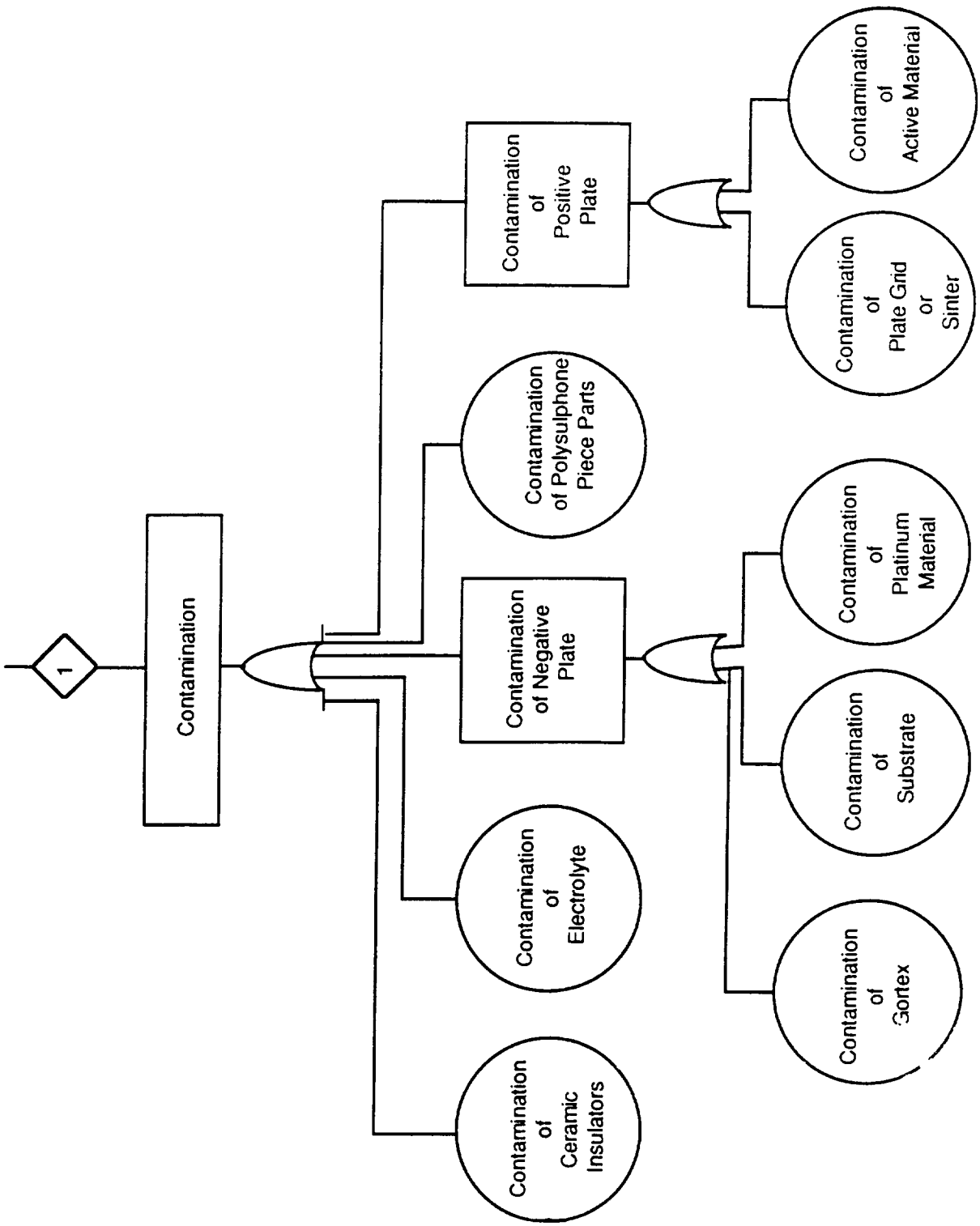
1
Contamination
Contamination of Positive Plate
Contamination of Active Material
Contamination of Plate Grid or Sinter
Contamination of Polysulphone Piece Parts
Contamination of Negative Plate
Contamination of Platinum Material
Contamination of Substrate
Contamination of Electrolyte
Contamination of Ceramic Insulators
Contamination of Gortex

FIGURE 8

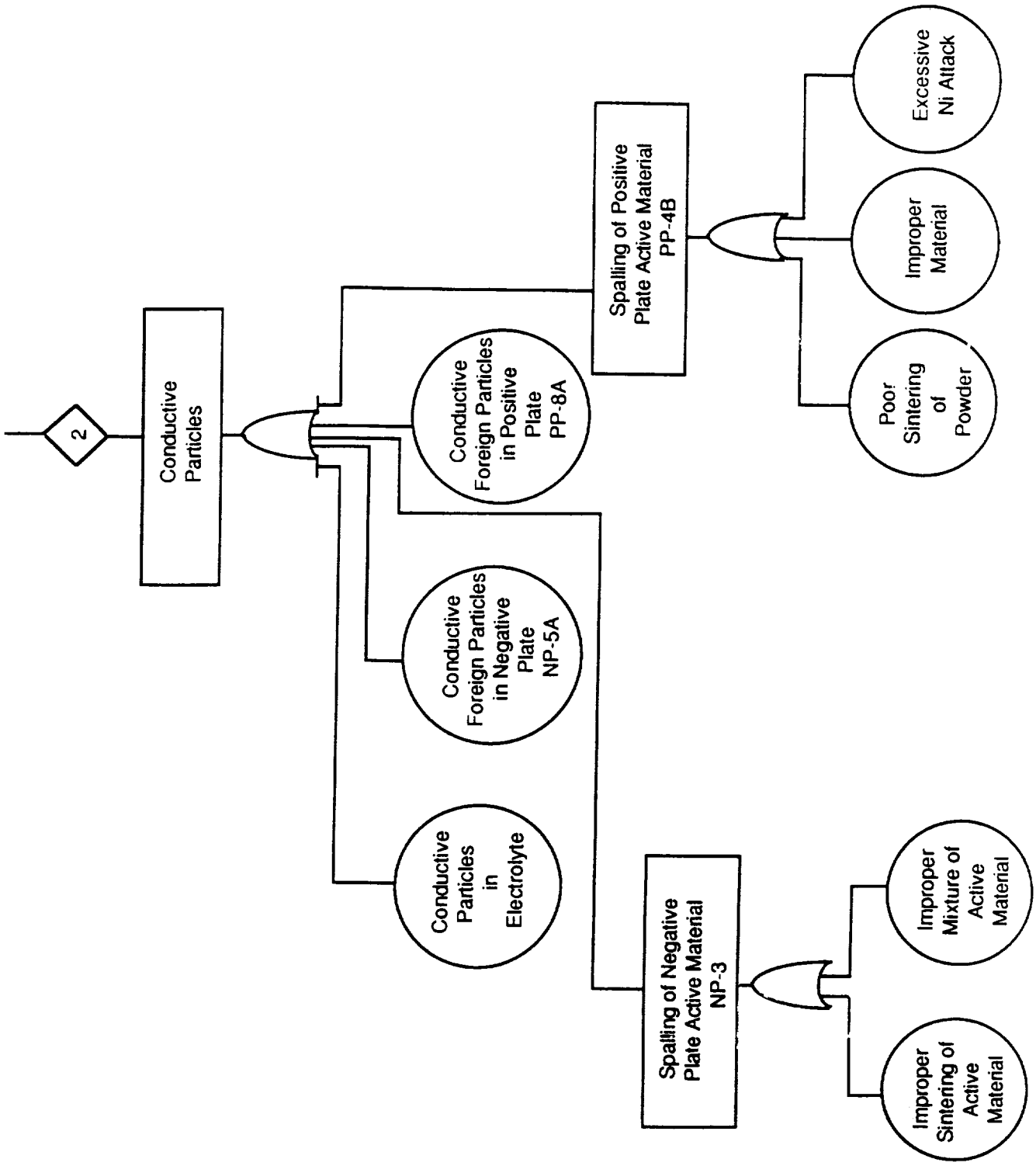
2
Conductive Particles
Conductive Foreign Particles in Positive Plate PP-8A
Conductive Foreign Particles in Negative Plate NP-5A
Conductive Particles in Electrolyte
Spalling of Positive Plate Active Material PP-4B
Excessive Ni Attack
Improper Material
Poor Sintering of Powder
Spalling of Negative Plate Active Material NP-3
Improper Mixture of Active Material
Improper Sintering of Active Material

FIGURE 9

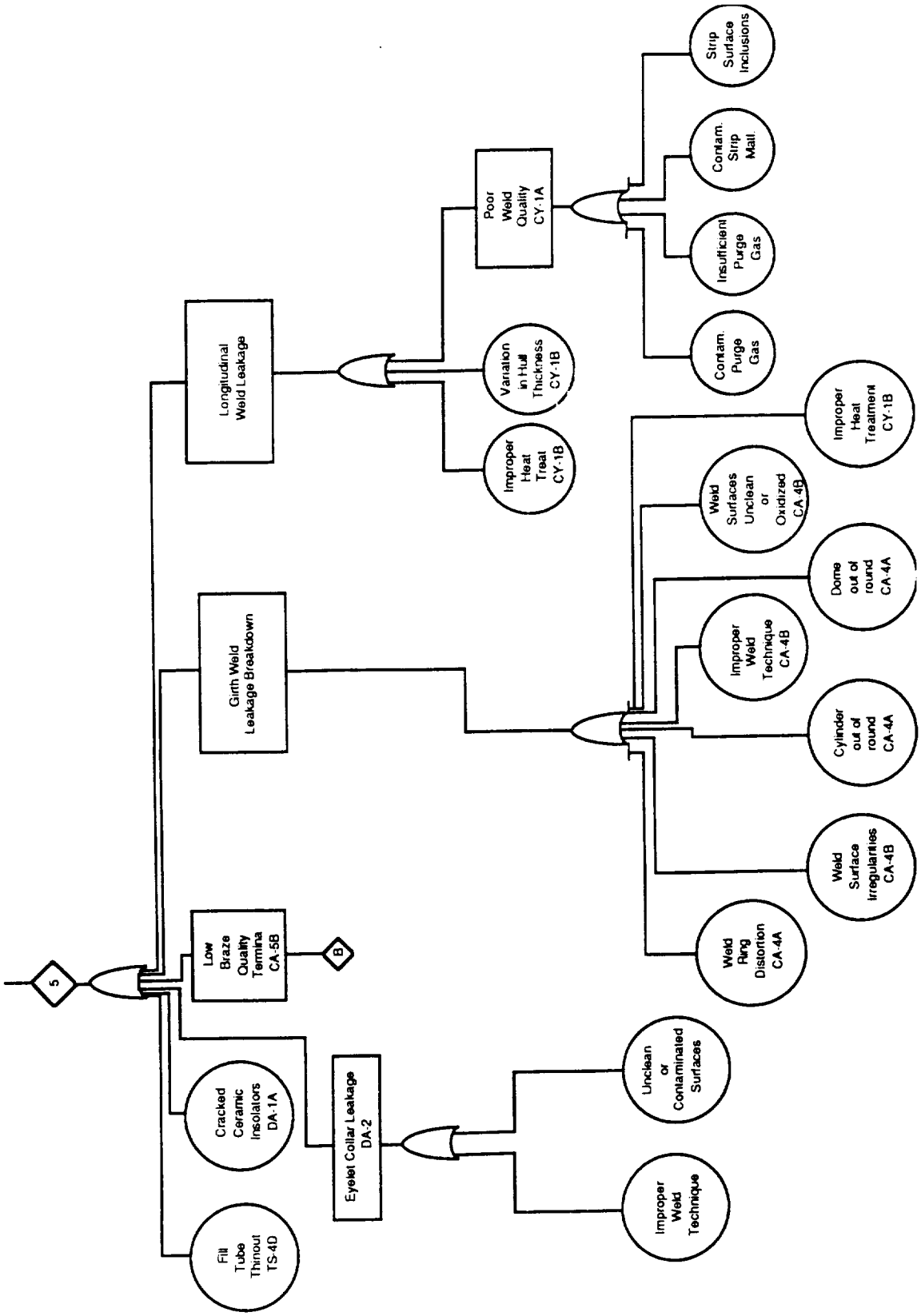
5
Low Braze Quality Termina CA-5B
8
Cracked Ceramic Insolators DA-1A
Fill Tube Thinout TS-4D
Eyelet Collar Leakage DA-2
Unclean or Contaminated Surfaces
Improper Weld Technique
Girth Weld Leakage Breakdown
Weld Ring Distortion CA-4A
Weld Surface Irregularities CA-4B
Cylinder out of round CA-4A
Improper Weld Technique CA-4B
Dome out of round CA-4A
Weld Surfaces Unclean or Oxidized CA-4B
Improper Heat Treatment CY-1B
Longitudinal Weld Leakage
Improper Heat Treat CY-1B
Variation in Hull Thickness CY-1B
Poor Weld Quality CY-1A
Contam. Purge Gas
Insufficient Purge Gas
Contam. Strip Mall.
Strip Surface Inclusions

FIGURE 10

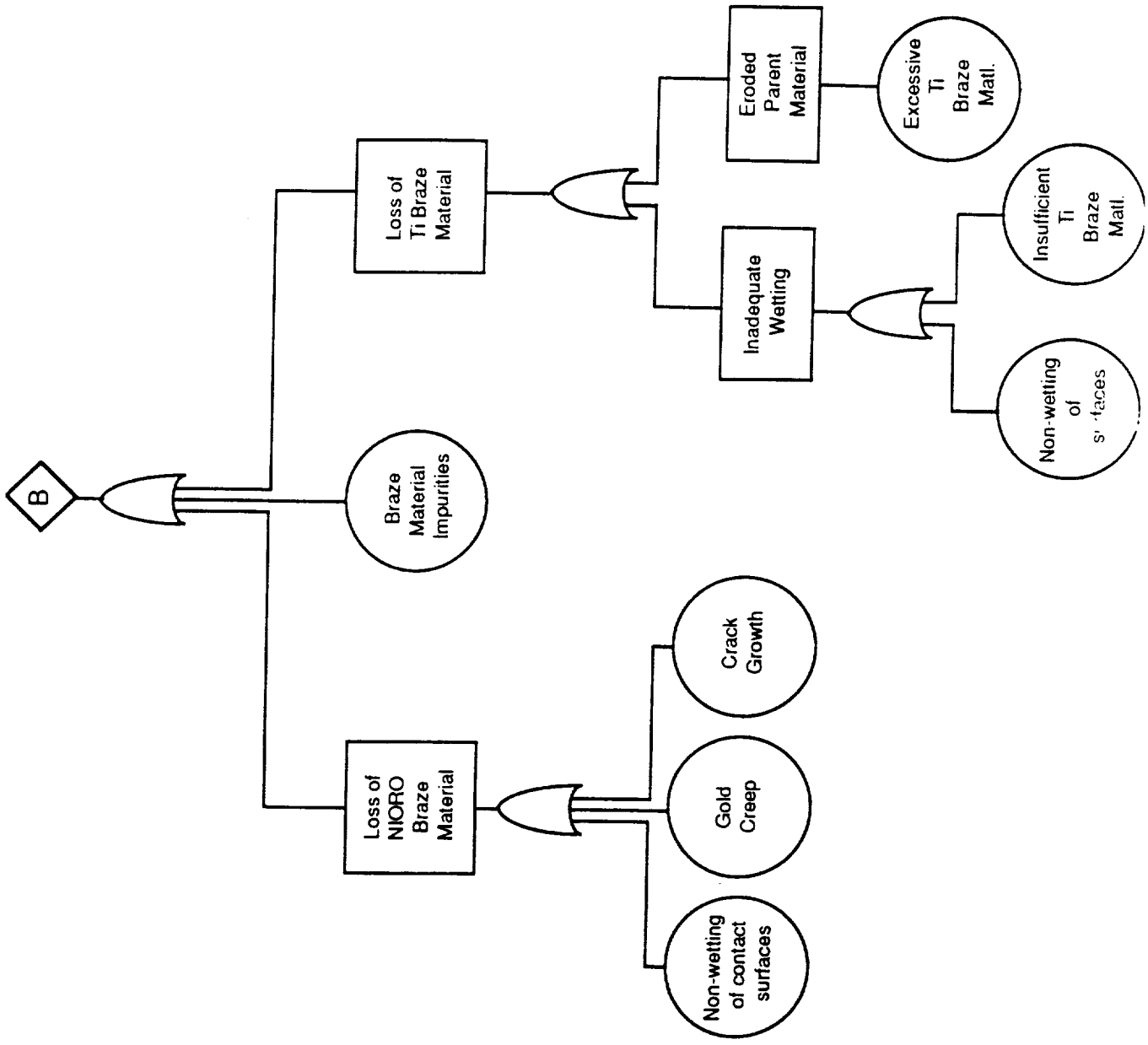
B
Loss of Ti Braze Material
Eroded Parent Material
Excessive Ti Braze Matl.
Inadequate Wetting
Insufficient Ti Braze Matl.
Non-wetting of surfaces
Braze Material Impurities
Loss of NiORO Braze Material
Crack Growth
Gold Creep
Non-wetting of contact surfaces

FIGURE 11

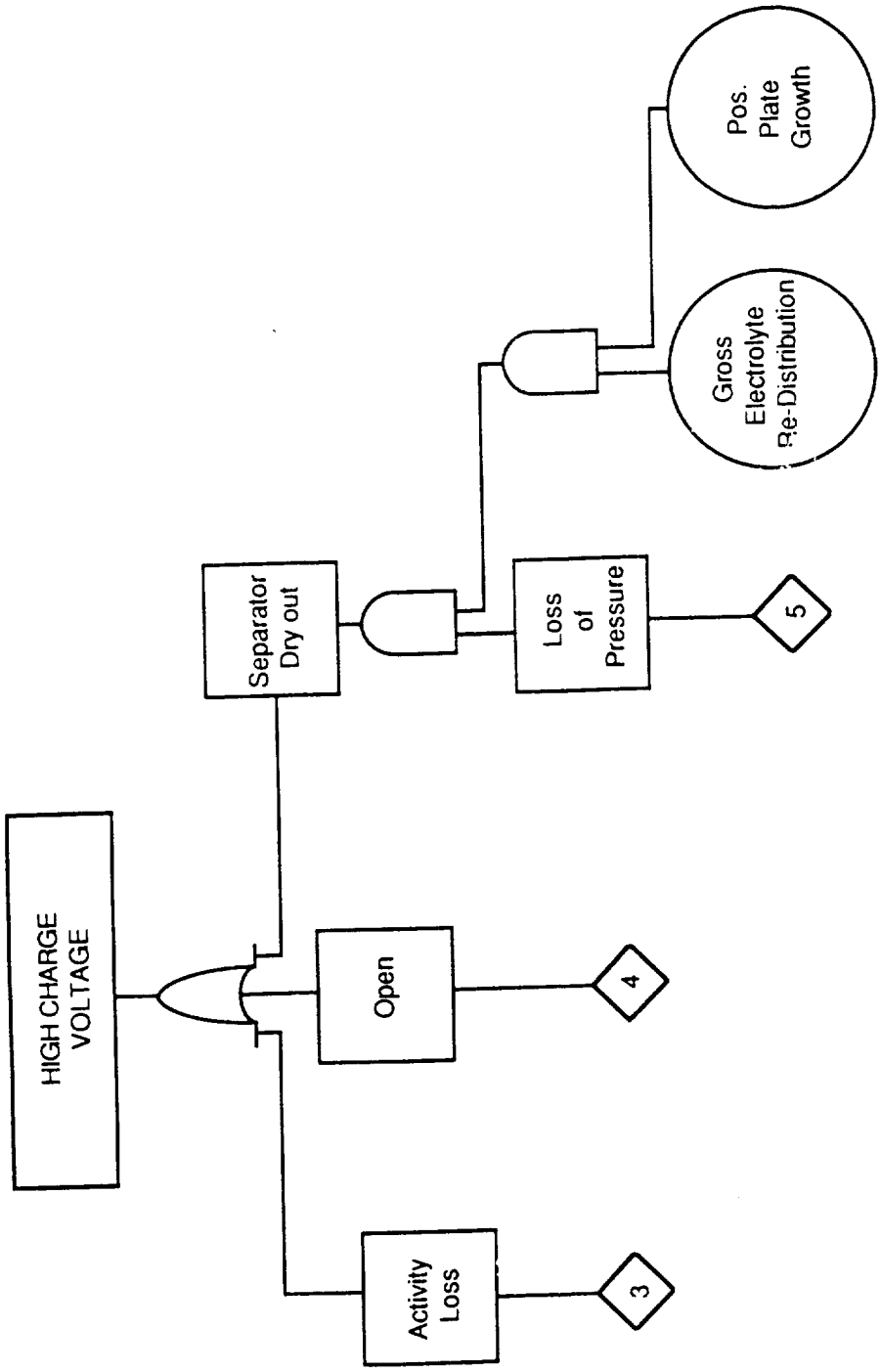
Pos.
Plate
Growth
Gross
Electrolyte
Re-Distribution
Separator
Dry out
Loss
of
Pressure
5
HIGH CHARGE
VOLTAGE
Open
4
Activity
Loss
3

FIGURE 12

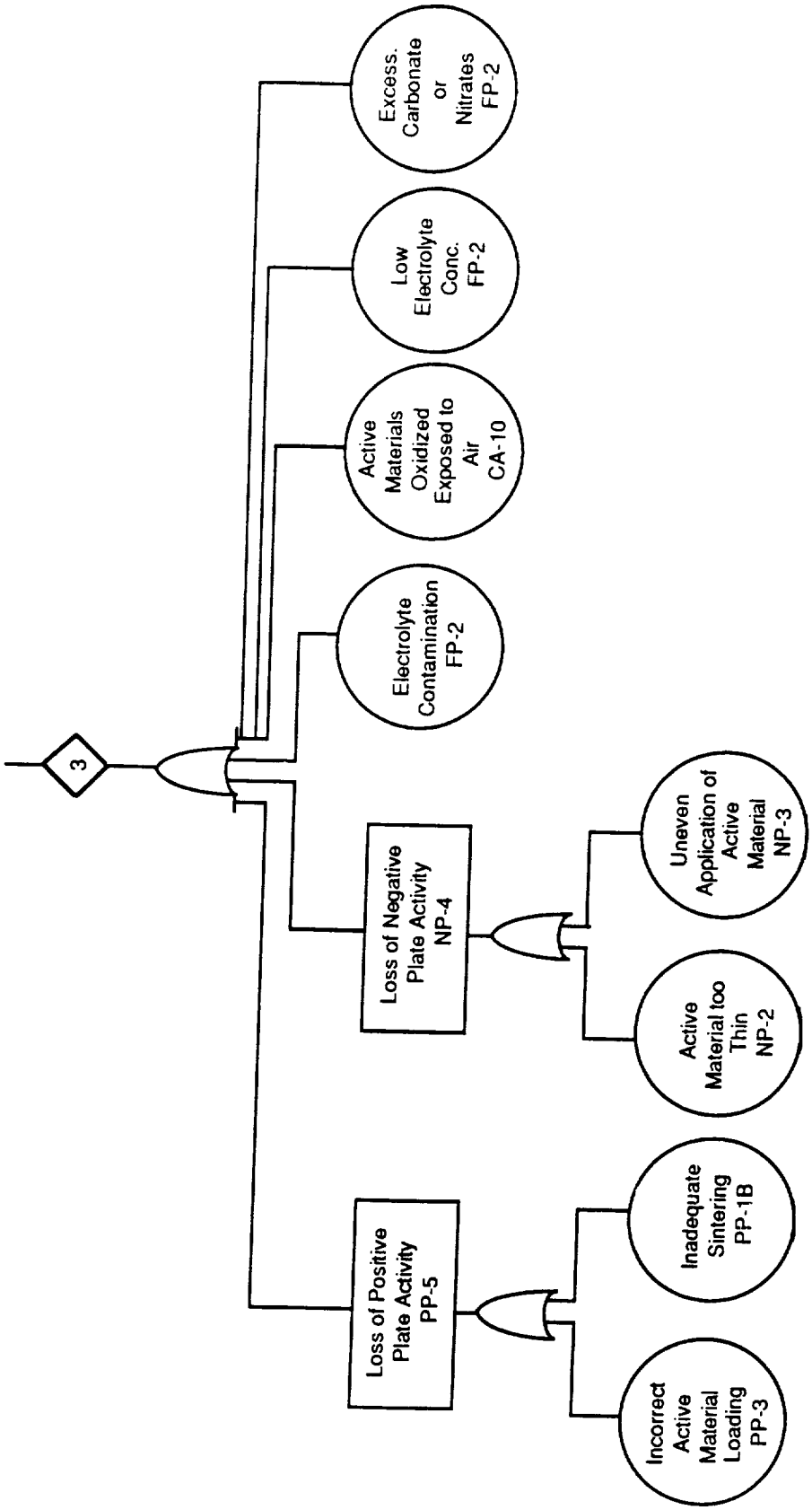
3
Excess. Carbonate or Nitrates FP-2
Low Electrolyte Conc. FP-2
Active Materials Oxidized Exposed to Air CA-10
Electrolyte Contamination FP-2
Loss of Negative Plate Activity NP-4
Uneven Application of Active Material NP-3
Active Material too Thin NP-2
Loss of Positive Plate Activity PP-5
Inadequate Sintering PP-1B
Incorrect Active Material Loading PP-3

FIGURE 13

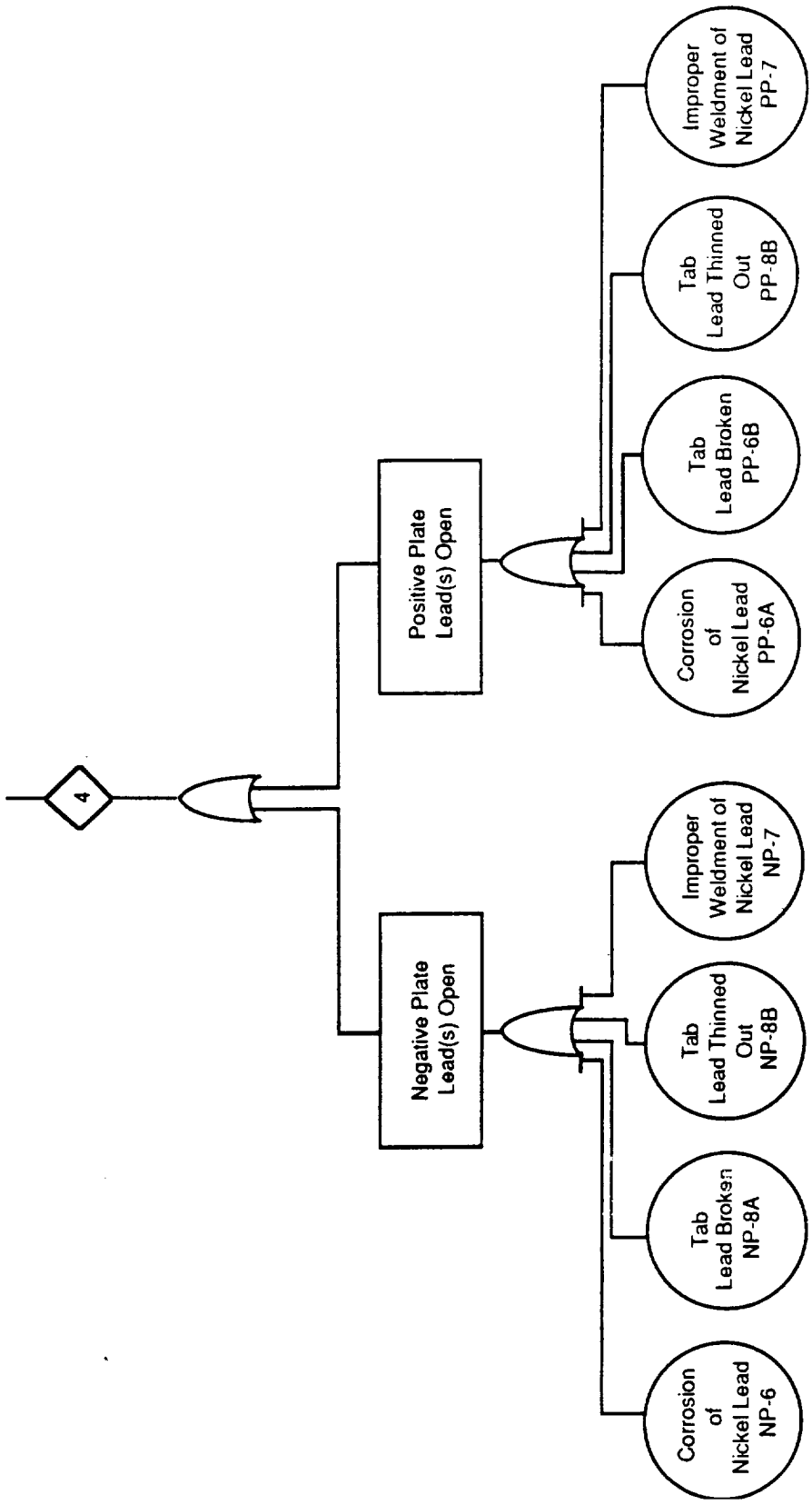
4
Positive Plate Lead(s) Open
Negative Plate Lead(s) Open
Corrosion of Nickel Lead PP-6A
Tab Lead Broken PP-6B
Tab Lead Thinned Out PP-8B
Improper Weldment of Nickel Lead PP-7
Corrosion of Nickel Lead NP-6
Tab Lead Broken NP-8A
Tab Lead Thinned Out NP-8B
Improper Weldment of Nickel Lead NP-7

FIGURE 14

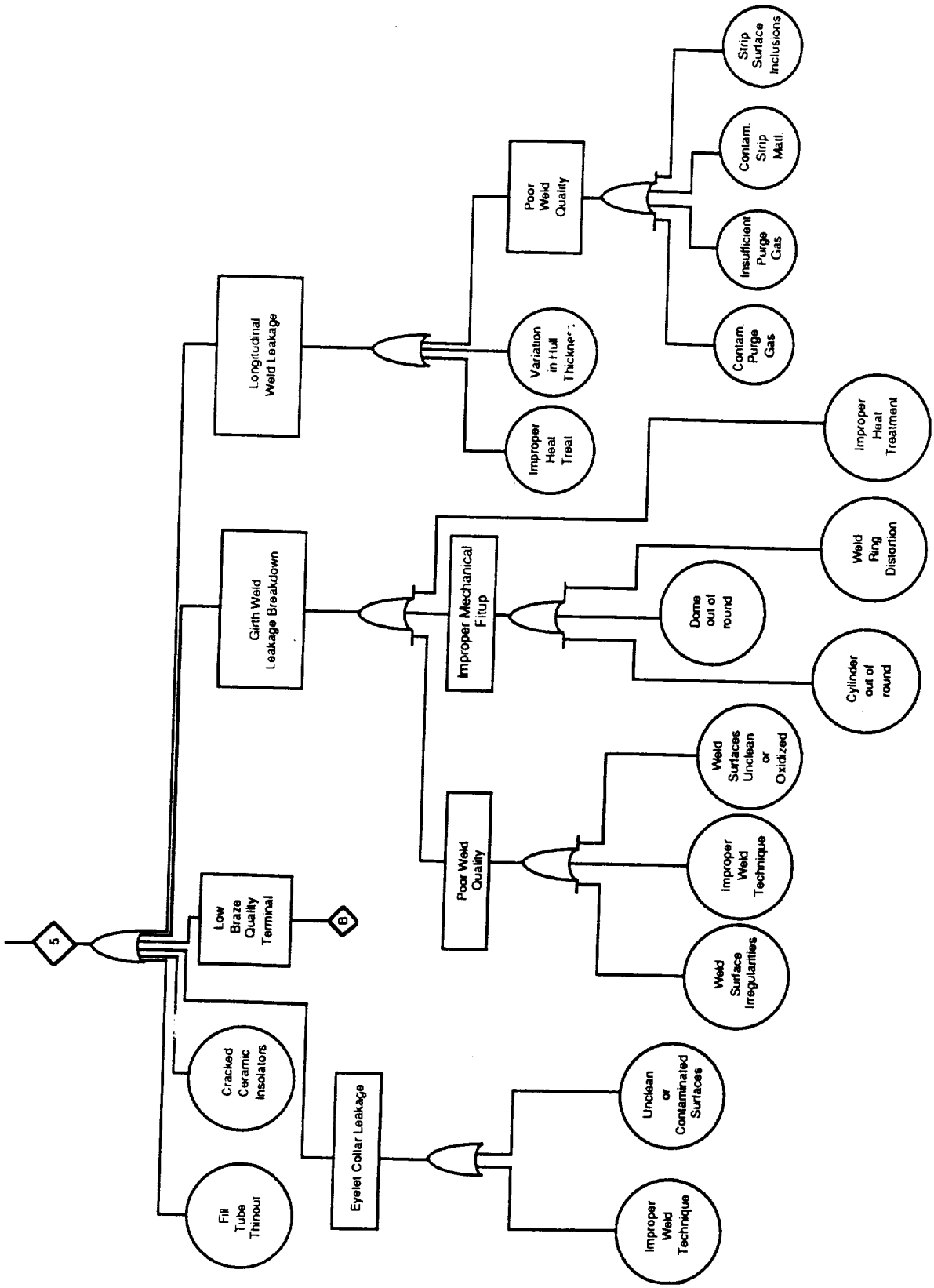
5
Low Braze Quality Terminal
B
Longitudinal Weld Leakage
Poor Weld Quality
Strip Surface Inclusions
Contam. Strip Matl
Insufficient Purge Gas
Contam. Purge Gas
Variation in Hat Thickness
Improper Heat Treat
Girth Weld Leakage Breakdown
Improper Mechanical Fitup
Improper Heat Treatment
Weld Ring Distortion
Dome out of round
Cylinder out of round
Poor Weld Quality
Weld Surfaces Unclean or Oxidized
Improper Weld Technique
Weld Surface Irregularities
Cracked Ceramic Insulators
Eyelet Collar Leakage
Unclean or Contaminated Surfaces
Fill Tube Throat
Improper Weld Technique

FIGURE 15

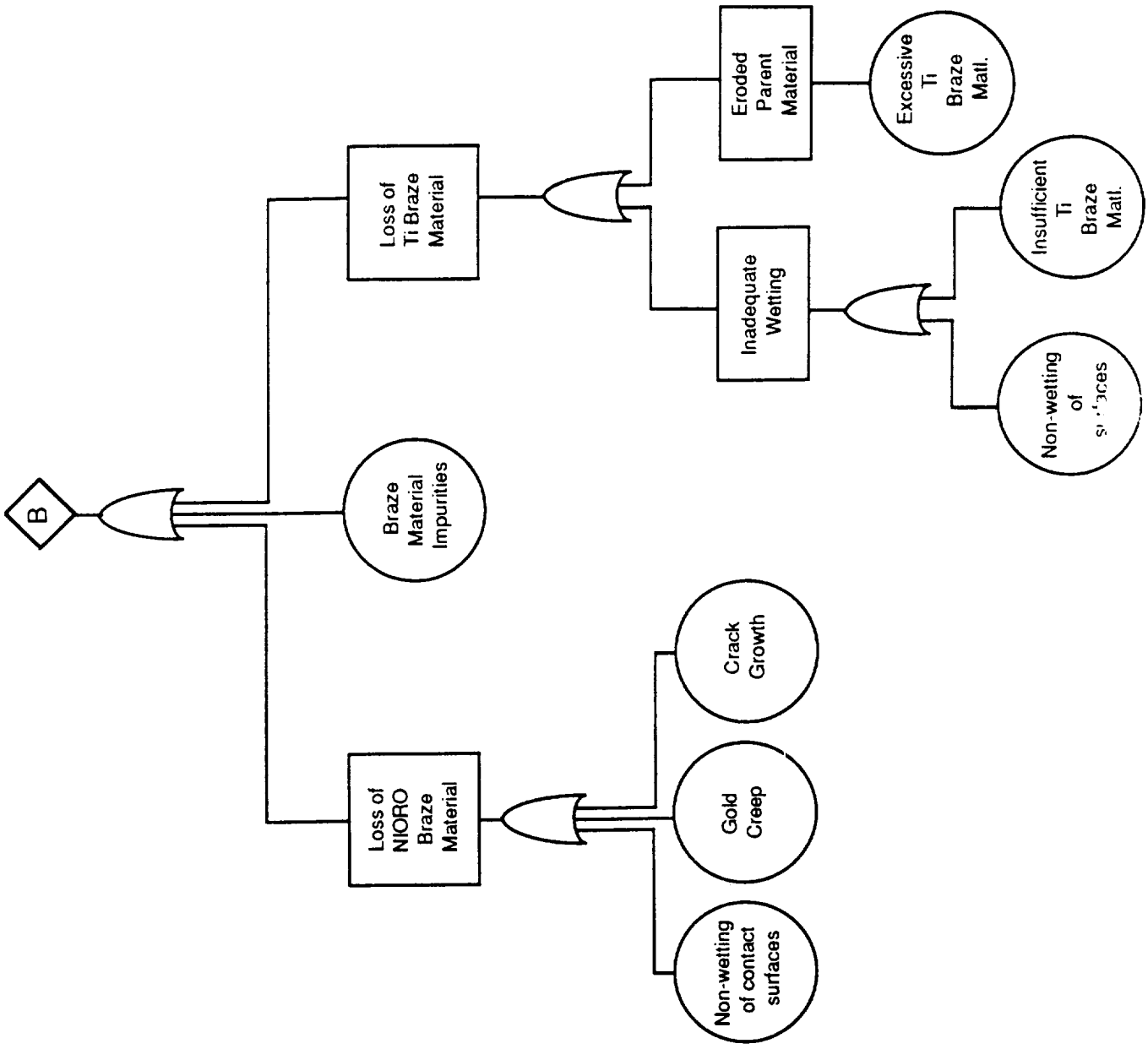
B
Braze Material Impurities
Loss of Ti Braze Material
Eroded Parent Material
Excessive Ti Braze Matl.
Inadequate Wetting
Insufficient Ti Braze Matl.
Non-wetting of
Loss of NiORO Braze Material
Crack Growth
Gold Creep
Non-wetting of contact surfaces

FIGURE 16

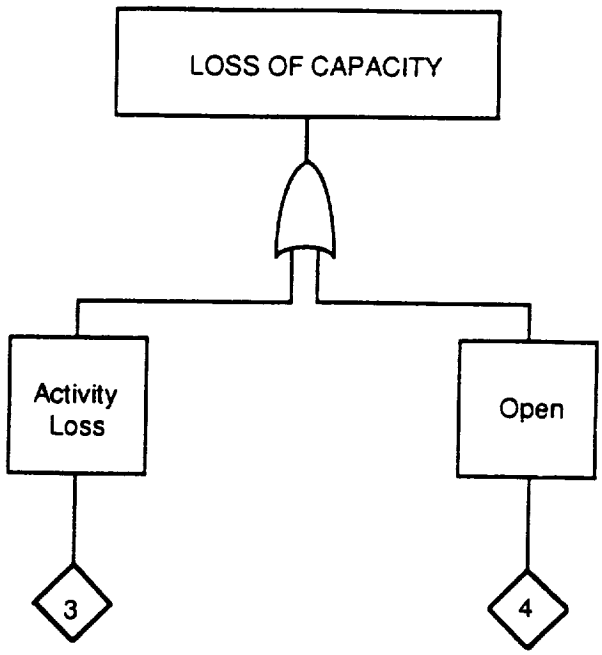

FIGURE 17

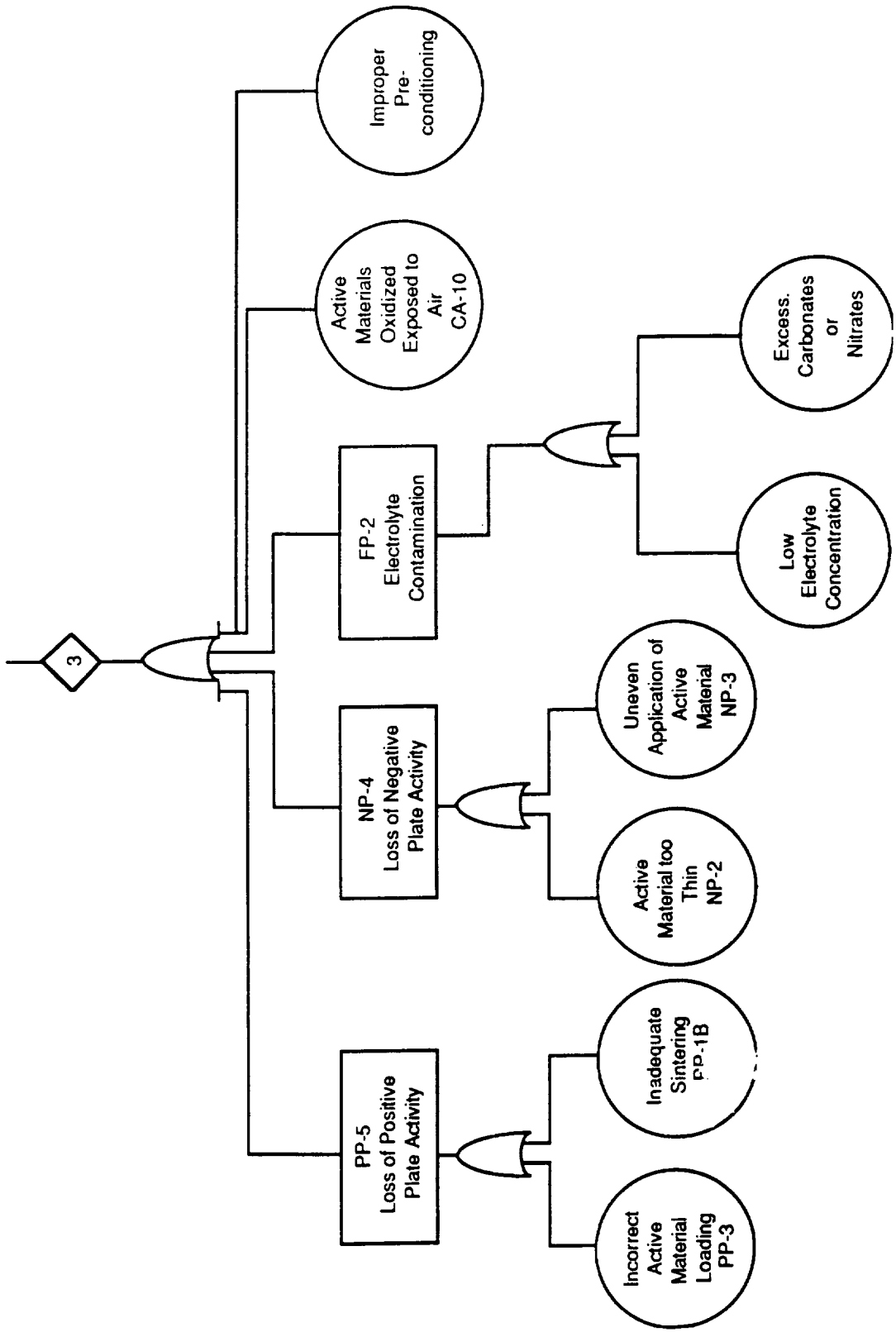
3
Improper Pre-conditioning
Active Materials Oxidized Exposed to Air CA-10
FP-2 Electrolyte Contamination
Excess. Carbonates or Nitrates
Low Electrolyte Concentration
NP-4 Loss of Negative Plate Activity
Uneven Application of Active Material NP-3
Active Material too Thin NP-2
PP-5 Loss of Positive Plate Activity
Inadequate Sintering PP-1B
Incorrect Active Material Loading PP-3

FIGURE 18

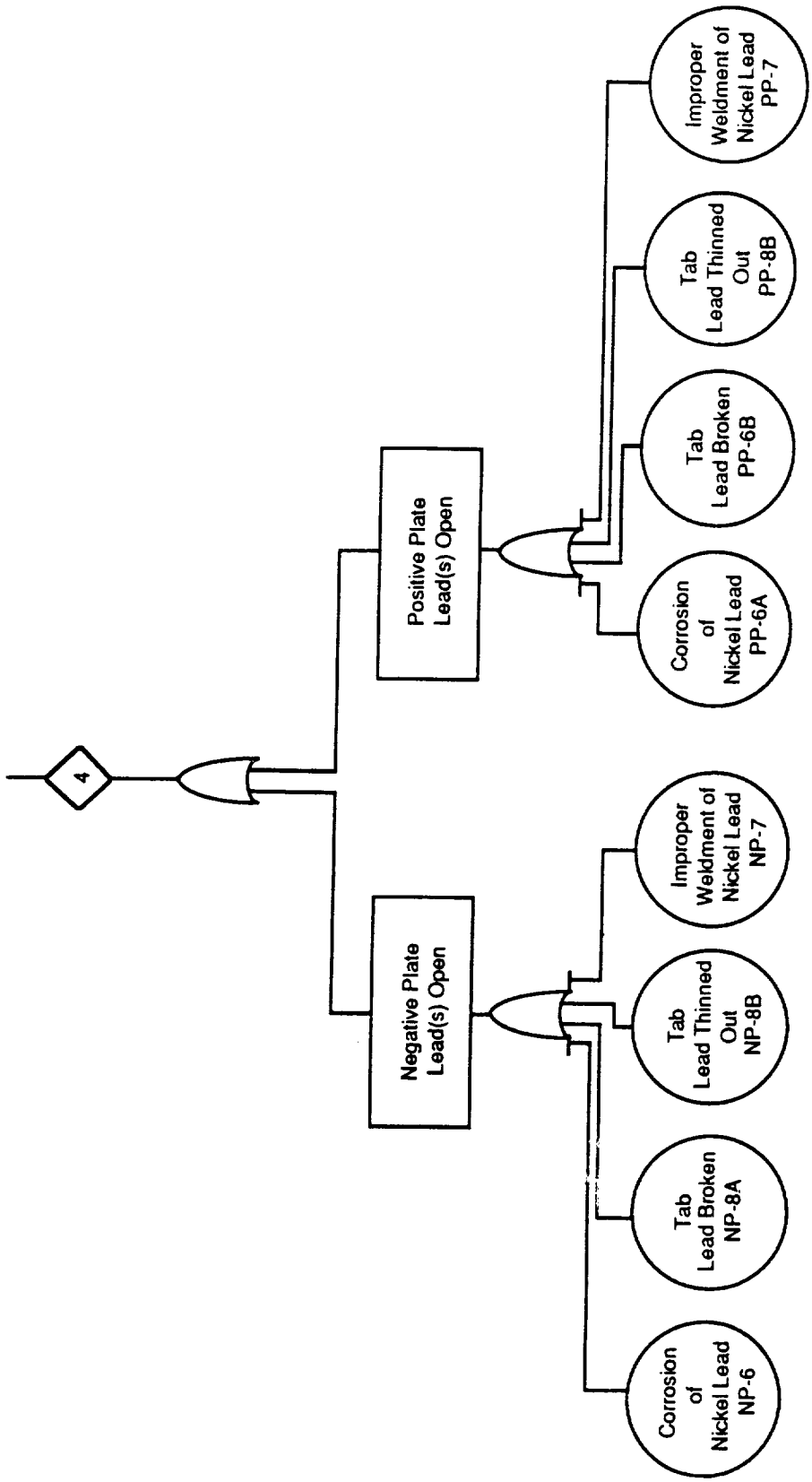
4
Positive Plate Lead(s) Open
Negative Plate Lead(s) Open
Improper Weldment of Nickel Lead PP-7
Tab Lead Thinned Out PP-8B
Tab Lead Broken PP-6B
Corrosion of Nickel Lead PP-6A
Improper Weldment of Nickel Lead NP-7
Tab Lead Thinned Out NP-8B
Tab Lead Broken NP-8A
Corrosion of Nickel Lead NP-6

FIGURE 19

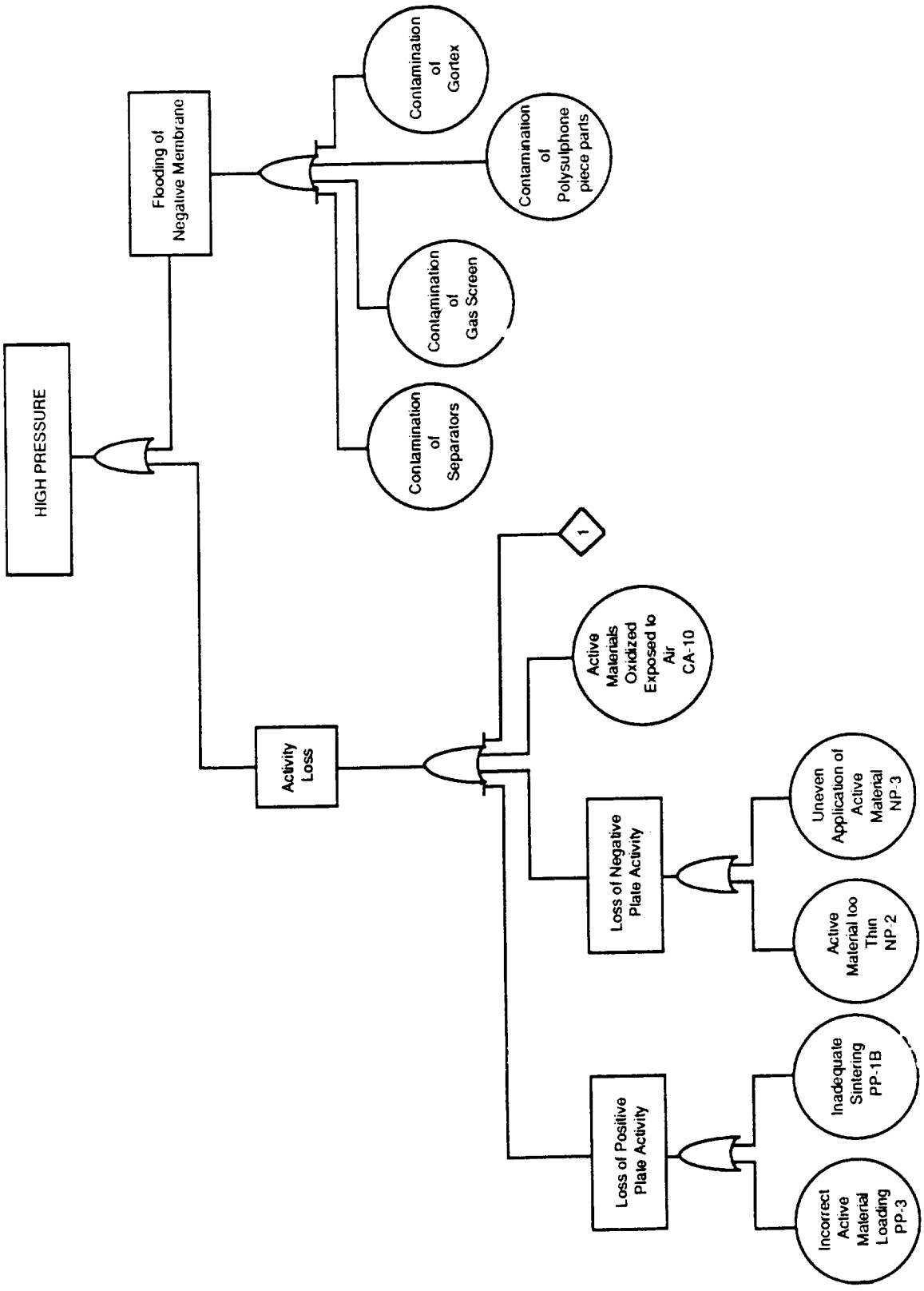
HIGH PRESSURE
Flooding of Negative Membrane
Contamination of Gortex
Contamination of Polysulphone piece parts
Contamination of Gas Screen
Contamination of Separators
Activity Loss
1
Active Materials Oxidized Exposed to Air CA-10
Loss of Negative Plate Activity
Uneven Application of Active Material NP-3
Active Material too Thin NP-2
Loss of Positive Plate Activity
Inadequate Sintering PP-1B
Incorrect Active Material Loading PP-3

FIGURE 20

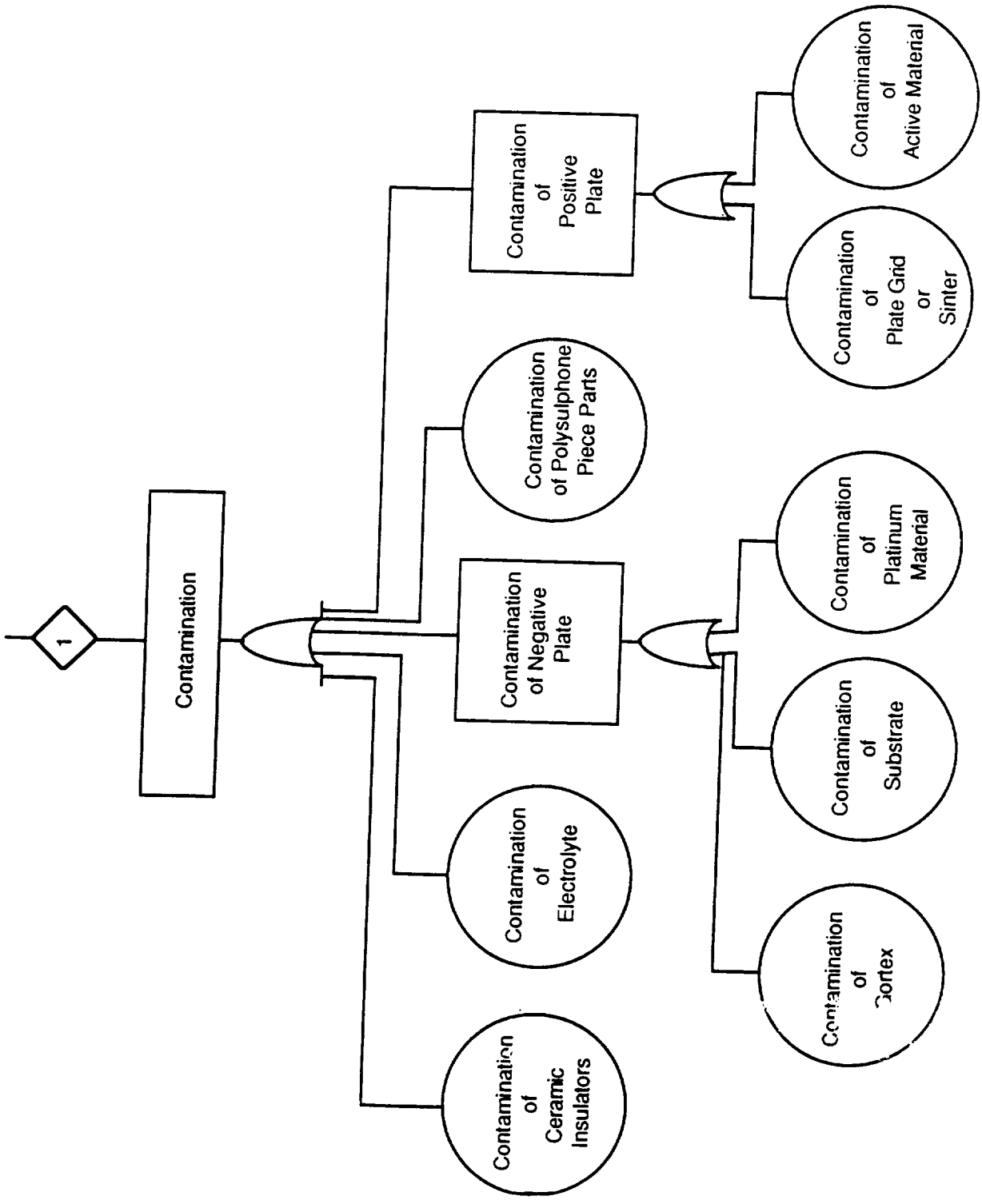
1
Contamination
Contamination of Positive Plate
Contamination of Active Material
Contamination of Plate Grid or Sinter
Contamination of Polysulphone Piece Parts
Contamination of Negative Plate
Contamination of Platinum Material
Contamination of Substrate
Contamination of Electrolyte
Contamination of Ceramic Insulators

FIGURE 21

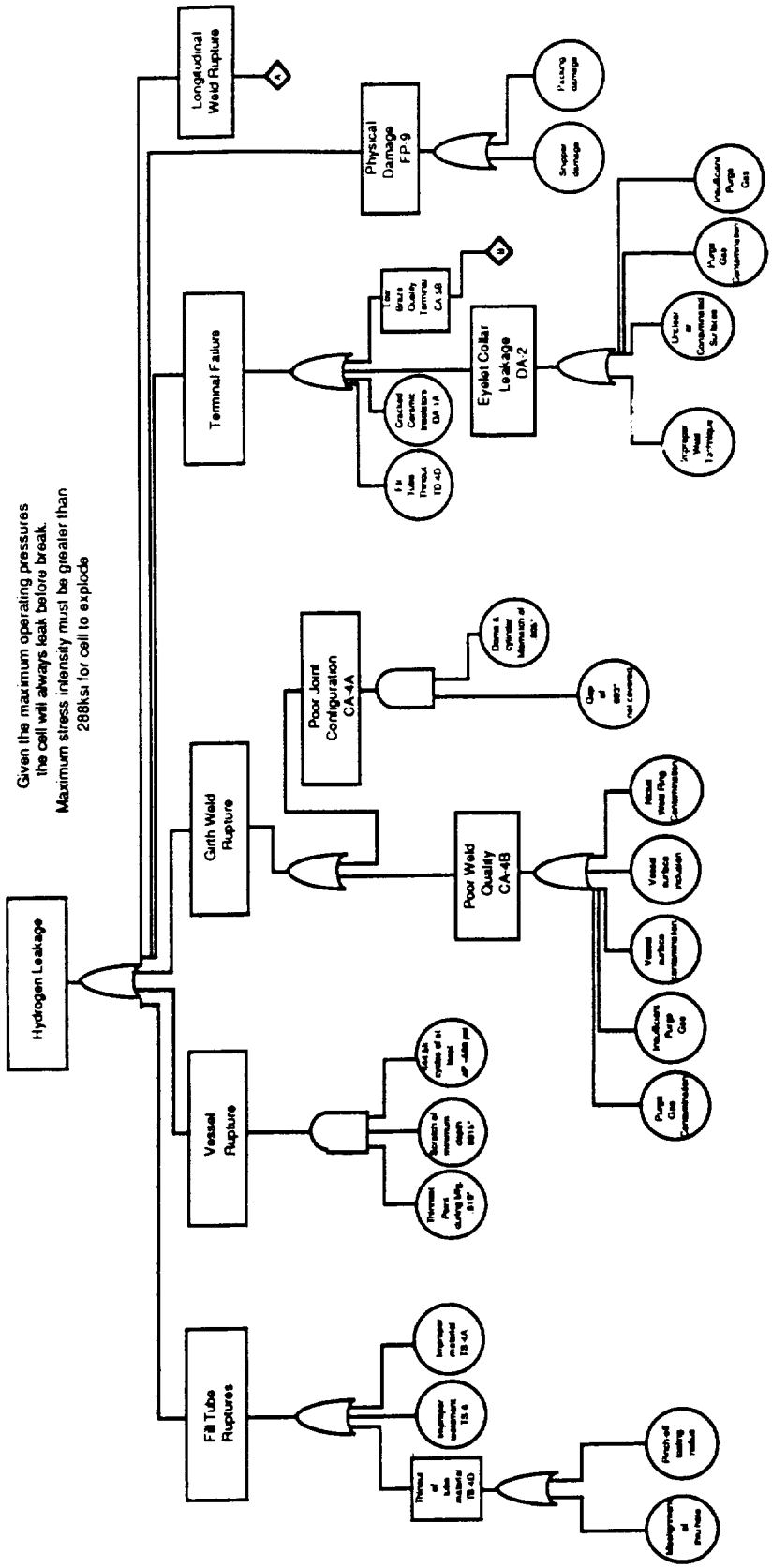
Given the maximum operating pressures
the cell will always leak before break.
Maximum stress intensity must be greater than
288ksi for cell to explode
Hydrogen Leakage
Longitudinal Weld Rupture
Physical Damage FP-9
Terminal Failure
Eyelet Collar Leakage DA-2
Girth Weld Rupture
Poor Joint Configuration CA-4A
Poor Weld Quality CA-4B
Vessel Rupture
Fill Tube Ruptures

FIGURE 22

Failure Modes and Effects Analysis on Gates NiH_2 Battery for LEO Mission

FMEA NO. CA-4B
Critical Item (Yes/No) Yes
Item Name: Girth weld
Part Number: 149C1930AJ1
Quantity: 1
Hardware Location: (Internal)
System: NiH2 Battery
Subsystem: Cell assembly
Reference Designator: _____
Hardware (Including Redundancy)
Operating Verification:
(A) Checkout
(1) Prelaunch PASS
(2) On Orbit FAIL
(B) Detectability PASS
(Appropriate Mission Phases)

Document Number: RAC NiH2 Battery FMEA
Document/Revision Date: 14 June 1991
Critical Category: 1
Failure Effect Phase
X (A) Prelaunch
X (B) Transportation
X (C) Assembly
X (D) Permanently Manned Capability (PMC)
Is Function Restorable on Orbit? Battery Cell Only
ORU Level: TBD
Part Name: _____
Part Number: _____
ORU Failure Detectability: Yes TBD
_____
EVA Required (Yes/No): TDB

Reliability Analysis Center	Gates Battery
Prepared By: D. Rash Approved By: G. Ebel	Approved By: _____ Approved By: _____

Function: Girth weld
Failure Mode: Poor weld quality (cracks, inclusions, low strength, porous)

Failure Cause(s): Improper material choices. Improper weld techniques; Irregularities in weld surfaces; Weld surfaces contaminated; Weld gas contaminated; Inadequate purge gas flow

Failure Detection/Verification: Physical, visual, pressure and leakage tests
Correction Action: (A) Short Term: Article inspection
(B) Long Term: Control welding process

Time to Effect: Days

Failure Effect On: (A) Crew/TBD
(B) Mission Support _____
(C) System Loss of capacity
(D) Interfaces _____

Rational for Acceptability: (Note: Rational for Acceptability is applicable to CIL Items only)
(A) Design Safety factor of 3 for burst/operationg pressure & safety factor of 4 for burst/operating cycles
(B) Test Hydrogen leak, chemical leak, cycle, burst and proof tests
(C) Inspection First article and first piece _____
(D) Failure History _____
(E) Operations _____
(F) Maintainability N/A _____

Remarks/Hazards: HAZARD POTENTIAL - Leakage of Hydrogen

FIGURE 23

Establishing Parity with the FMECA

An example of a completed failure mode effects analysis worksheet (Figure 23) is provided to demonstrate how the failure causes are attributed to fault events, in this case Girth Weld Breakdown. The numbering system has been assigned to manufacturing flow steps and the example is FMEA number CA-4B. The failure mode corresponds directly to an event that has three distinct events associated to the upper level event.

Conclusion

The decision process for either qualitative or quantitative analyses is tempered by our view of reality and some model of our system under anlaysis; and, further constrained by our expectations of the external boundaries and robustness of the design. The Fault Tree Analysis is not a stand alone technique due to the top down approach which presupposes the determination of all Top-level or Major fault events; however, the Fault Tree when in a graphic, visual format is an excellent tool for technical reviews. Fault Tree Analyses can be quantified in areas such as System Assessment, Confidence Analysis, and Sensitivity Analysis. The Qualitative Fault Tree Analysis for NiH_2 cells in LEO Mission identifies and analyzes five specific Top-Level failure events; quantification of this Fault Tree has already begun.

References

1) Fault Tree Handbook, NUREG-0492, U.S. Nuclear Regulator Commission, Washington, DC, (1981)

2) Fault Tree Analysis Application Guide, Reliability Analysis Center, Rome, NY, (1990).